

Development of an Intelligent Power Unit for the Civic Hybrid

Kazuhiko AITAKA*

Masaharu HOSODA*

Takuya NOMURA*

ABSTRACT

The Intelligent Power Unit (IPU) utilized in Honda's Civic Hybrid Integrated Motor Assist (IMA) system was developed with the aim of making every component lighter, more compact and more efficient than those in the former model. To reduce energy loss, inverter efficiency was increased by fine patterning of the Insulated Gate Bipolar Transistor (IGBT) chips, 12 V DC-DC converter efficiency was increased by utilizing soft-switching, and the internal resistance of the IMA battery was lowered by modifying the electrodes and the current collecting structure. These improvements reduced the amount of heat generated by the unit components and made it possible to combine the previously separate Power Control Unit (PCU) and battery cooling systems into a single system. Consolidation of these two cooling circuits into one has reduced the volume of the newly developed IPU by 42% compared to the former model.

Introduction

One major issue for the automotive industry in recent years is the reduction of CO₂ emissions by lowering automotive fuel consumption. One response to this issue has focused on hybrid systems that combine an engine with an electric motor. In 1999 Honda began to market the Insight, a vehicle installed with a newly developed, compact, lightweight IMA (Integrated Motor Assist) system. Now, Honda has developed an IPU (Intelligent Power Unit) for the IMA system fitted to the Civic Hybrid that entered the market last year, with the aim of further market penetration by hybrid cars. This paper introduces the various component technologies developed in order to achieve the lightweight, compact components necessary to make possible IMA installation in a 4-door sedan.

1. Development Aims of IPU for the Civic Hybrid

Development of the IPU to be equipped to the Civic 4-door sedan had as its goal being able to fit the IMA system while at the same time maintaining ease of vehicle use, including cabin comfort and trunk space of a conventional sedan. The basic concept was "maintaining seating room for five people and the appropriate amount of trunk space." In order to achieve these aims, the target was to compactly store the IPU – which is 40% smaller in volume than that of the Insight – behind the rear seats.

1.1. Smaller IPU

Figure 1 shows the IPU installed in the Insight. The previous mode's IPU volume was 138 L, the breakdown of which is shown below.

* Tochigi R&D Center

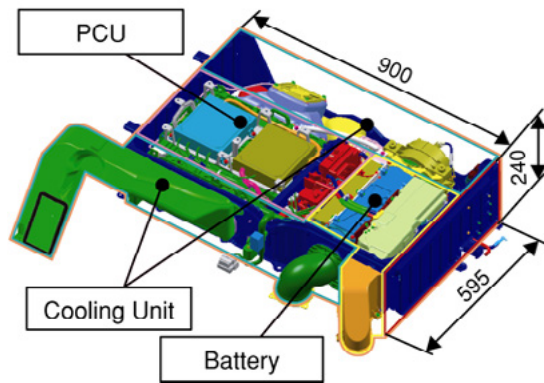


Fig. 1 Dimensions of Insight IPU

- Power Control Unit (PCU) 33 L (24%)
- Battery 43 L (31%)
- Cooling System 62 L (45%)

The target for the Civic Hybrid's IPU volume was set at 80 L, and the following targets were set for reducing components size.

- PCU 20%
- Battery 30%
- Cooling System 60%

1.2. Cooling System Integration

Focusing particularly on making the cooling system more compact, studies were made into integration of the cooling circuit, which conventionally are two separate systems, and integrating the battery and the PCU cooling. Giving consideration to the battery control temperature, the temperature of intake air, which is the coolant for battery cooling, must be at normal temperatures. Therefore, with the Civic Hybrid, the assumption is that cooling intake will be taken from inside the cabin and exhaust back to the cabin. In addition, the increase in air-conditioning load accompanying in-vehicle intake and exhaust and noise inside the vehicle were considered, so cooling airflow target was set at 90 m³/hr or lower. The cooling system required airflow for the Insight was as follows.

- Inverter 138 m³/hr
- 12 V DC-DC Converter 120 m³/hr
- Battery 60 m³/hr

With the integration of the cooling systems, it was necessary to reduce the inverter and 12 V DC-DC converter required airflow to no more than 90 m³/hr. With the previous model, because the PCU cooling air was taken from outside the vehicle, giving full consideration to high temperature environments such under a blazing sun, it was necessary to estimate a high intake air temperature. However, because intake air is taken from inside the vehicle when the cooling systems are integrated, a drop in cooling intake air temperature can be expected. That is to say, it is possible to reduce the amount of required airflow. At the same time, it is of course also necessary to reduce the amount of heat generated, by improving the efficiency of each PCU component. Therefore, a study was made, investigating whether or not it would be possible to integrate the two conventional cooling systems into one, by reducing intake air temperature and improving device efficiency.

1.3. Measures to Increase in Assist and Regeneration Power

It was necessary to make additional changes from the Insight including measures to increase by 30% in assist and regeneration power with an increase in vehicle weight and the addition of a cylinder idling system (CIS). In this aspect, improved efficiency in each IPU component device was required, and was an important issue in this development project. In particular, heat generated by an increase in battery input and output was an issue. Therefore, in response, at the same time as maintaining the target maximum airflow amount with the aforementioned cooling system integration, measures were taken to increase the cooling airflow by 50% and to reduce the amount of heat generated by reducing battery internal resistance by 20% over the previous model.

2. Power Control Unit

In order to actualize the installation of the IPU behind the rear seats, it was necessary to reduce the size of the PCU by approximately 20% and to reduce the inverter and 12 V DC-DC converter loss. The following actions necessary to resolve these technological issues are listed below.

- Integration of inverter and pre-driver into one small component
- Reduction in loss by fine patterning of the Insulated Gate Bipolar Transistor (IGBT) chips inside the inverter
- Size reduction through reducing capacitor loss and a high heat-radiation structure
- Size reduction with reduced loss by adopting a soft switching 12 V DC-DC converter control method.

As a result of the above technological developments, the PCU volume was 26.8 L, in comparison to the Insight's 33 L, and a 20% reduction was achieved. Figure 2 shows the Civic Hybrid's PCU.

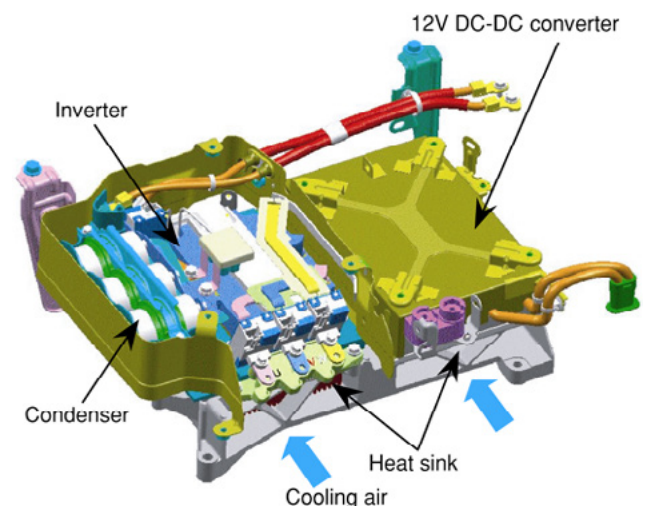


Fig. 2 Power Control Unit

2.1. Inverter

In order to achieve a smaller, lighter-weight inverter with reduced loss, development was carried out with the introduction of various new technologies for each inverter component device. Details are explained below.

2.1.1. Integration of inverter and pre-driver

The following modifications were made to the inverter that controls motor drive.

- (1) Custom IC for IGBT element drive circuit
- (2) Software processing of the safeguard function with the installation of a high-performance microcomputer
- (3) Simplification of interface circuit by allowing motor ECU communication through a serial interface.

With these new technologies a 39% size reduction and 28% weight reduction was achieved in comparison with the previous model. Figure 3 shows the inverter units in the Insight and the Civic Hybrid.

In addition, conventionally, protection against chip excessive heat is carried out when temperature is detected by a thermistor placed near the IGBT chips. However, with this newly developed product, there is a temperature sensor above the IGBT chips increasing temperature detection responsiveness.

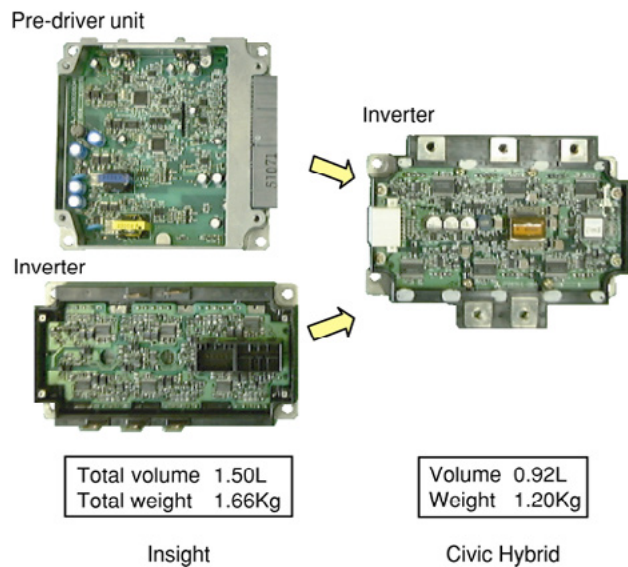


Fig. 3 Inverter unit

2.1.2. Reduction in loss with IGBT chip fine patterning

Figure 4 shows the cell pattern of the IGBT chips that are inverter power elements. By making the cell pattern finer than on the conventional model, approximately three times the number of cells can be mounted in the same chip area, thereby reducing the channel resistance R_{ch} for each unit area. Therefore, IGBT ON voltage drops and there is a maximum reduction in loss of 25% in comparison with the conventional.

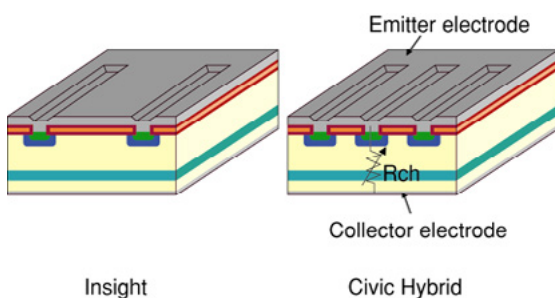


Fig. 4 Model of IGBT fine patterning

2.1.3. Smaller capacitor

Conventional electrolytic capacitor elements are held with resin thereby vibration resistance is maintained and heat is radiated. However, with this newly developed product, element heat radiation is promoted by direct contact between the bottom of the element and the aluminum case (Fig. 5) giving a 20% improvement in heat radiation in comparison with the previous model. In addition, due to a reduction in resistance from electrolyte and electrode foil etching modifications, element characteristic ESR (Equivalent Series Resistor) are improved and element generated heat is 18% less than the previous model. With the above modifications, a 30% size reduction and a 27% weight reduction were achieved in comparison with the previous capacitor.

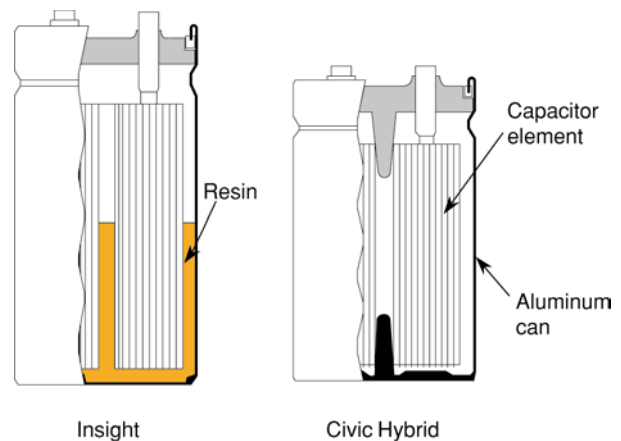


Fig. 5 Capacitor structure

2.1.4. Improvements to inverter efficiency

With the above technologies, inverter efficiency is improved in the total motor drive condition range and loss is reduced. Figure 6 is a graph showing inverter efficiency in relation to motor speed.

In addition, Fig. 7 is a map of inverter efficiency against motor speed and torque. It is clear from plotting on this graph the motor speed and torque sampling data from actual driving that it is the inverter high efficiency range that is mainly used. Energy loss reduction due to efficiency improvements will also contribute to improved fuel economy.

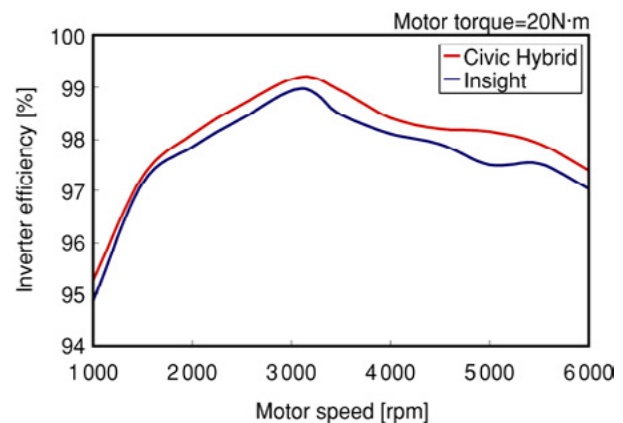


Fig. 6 Inverter efficiency

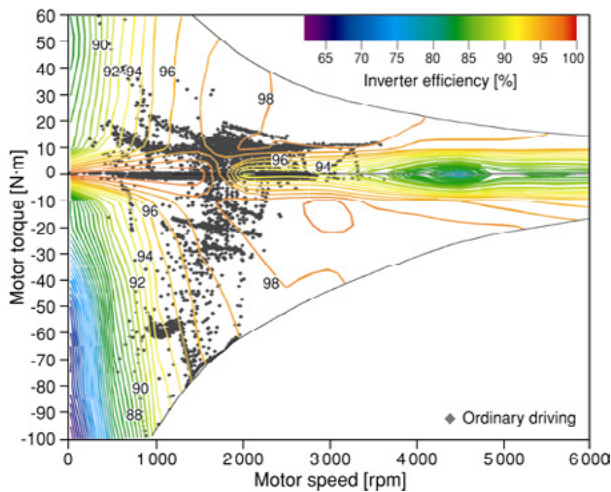


Fig. 7 Inverter efficiency map

2.2. 12 V DC-DC Converter

By adopting, for this 12 V DC-DC converter, a soft-switching system rather than the conventional hard-switching system, loss is reduced. Figure 8 is an outline operation diagram.

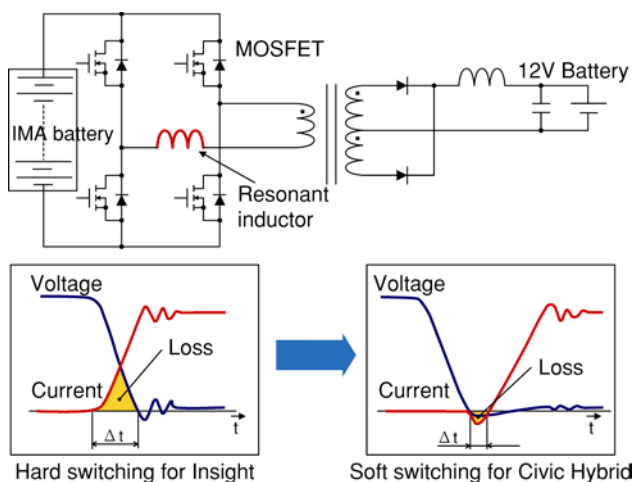


Fig. 8 12 V DC-DC converter circuit

In the switching operation of the MOSFET (Metal Oxide Semiconductor Field Effect Transistor) that drives the transformer, a resonant inductor is added to the path of the current that flows to the transformer through MOSFET from the IMA battery when MOSFET is ON. By controlling switching timing, voltage between MOSFET drain sources and drain current overlap time is shortened, thereby reducing switching loss. As shown in Fig. 9, the adoption of the above soft-switching circuits actualizes an average efficiency improvement of 2% over the previous model. In addition, accompanying this technology, it is possible to simplify the parts inside the converter, achieving a 22% size reduction over the Insight, and a 9% weight reduction.

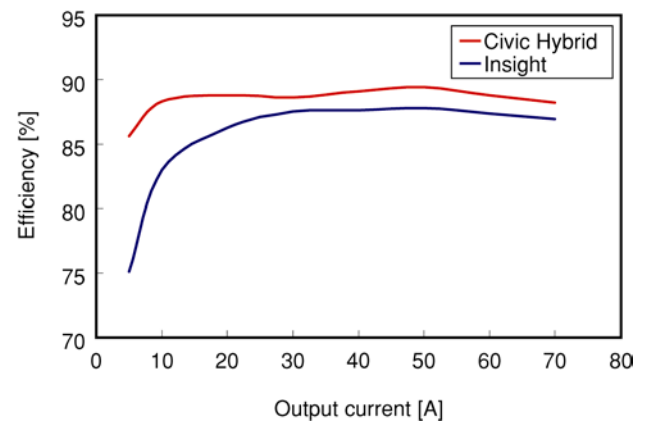


Fig. 9 12 V DC-DC converter efficiency

Figure 10 shows a map of 12 V DC-DC converter efficiency against input voltage from the IMA battery and output current to the 12 V battery. By making modifications to raise the actual use range efficiency shown on this graph, there is a reduction in loss during actual use. Accordingly, cooling with a smaller amount of airflow than required for the Insight is possible, and because there is a reduction in consumed energy, the device achieved a size reduction as well as improved fuel economy.

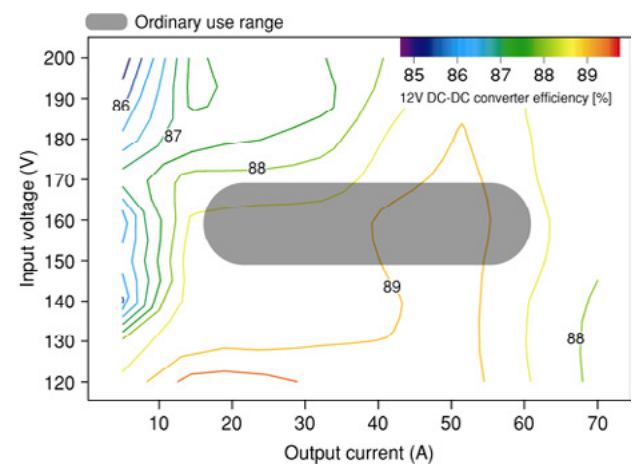


Fig. 10 12 V DC-DC converter efficiency map

3. IMA Battery

Changes from the Insight include an increase in vehicle weight and an engine cylinder idling system (CIS), meaning there is an increase in energy during regeneration. Because of the resulting increase in assist and regeneration power, that is to say, because the average battery input and output levels are larger during driving, it is expected that there will be an increase in battery-generated heat. Therefore, the following countermeasures were studied.

- (1) Reduce battery module internal resistance by approximately 20%
- (2) Increase battery cooling airflow by 50% of the previous mode.

Figure 11 shows the amount of heat generated and the heat balance during Insight and Civic Hybrid actual driving.

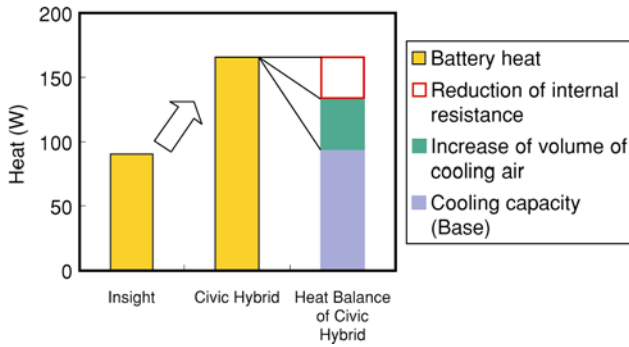


Fig. 11 Battery heat balance

The amount of heat generated was approximately 1.8 times that of the Insight, but with a battery internal resistance reduction of 20% and a cooling airflow increase of 50%, it is possible to keep battery temperature rise to the level over the previous model.

3.1. Battery Module

Modifications unique to the Civic Hybrid were made to the battery module, electrodes and current collector structure were revised, and in particular, a change to the shape of the current collecting plates reduced internal resistance. Figure 13 gives a comparison of current collecting plate shapes.

By changing the shape of these plates, there is an increase in the number of welds to the electrodes, and there is a leveling of collecting plate current density. Together with other internal battery modifications, there was a reduction in resistance of 19% compared with parts fitted to the Insight.



Fig. 12 IMA battery module

	Insight	Civic Hybrid
Positive current collector		
Negative current collector		
Number of welding points	84	118
Internal resistance	21mΩ	17mΩ (-19%)

Fig. 13 Current collecting plate

3.2. IMA Battery Box

With the aims of weight and size reduction, battery box component parts were revised.

- (1) By optimizing the layout of related parts around the battery box (battery ECU, harnesses, etc.), the box unit was made smaller.
- (2) Connecting part shapes were given optimum design and made smaller and lighter for the Civic Hybrid maintaining battery box strength the same or better than the previous model.

As a result of the above measures, in comparison with the Insight's battery box, box volume is 29.5% smaller, and weight is 5.6% lighter.

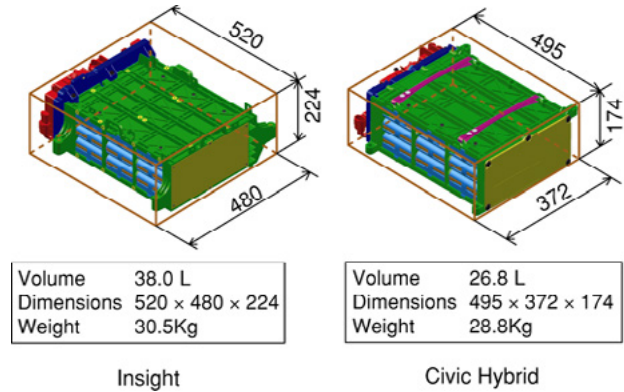


Fig. 14 IMA battery box

4. Integration of Cooling System

The Insight's IPU and its cooling circuit are shown in Fig. 15. In the previous model, the PCU cooling circuits were separate for the PCU and the battery system. The PCU system had cooling air taken from outside the vehicle, cooling the inverter and 12 V DC-DC converter, and then the air was exhausted outside the vehicle cabin. For the battery system, air was taken from inside the vehicle, the battery was cooled, and the air was exhausted back inside the vehicle. The cooling system occupied a large volume – almost 45% – of the total IPU. In contrast, with the Civic Hybrid a study was made of integrating the cooling circuits in order to achieve a cooling system that is 60% smaller.

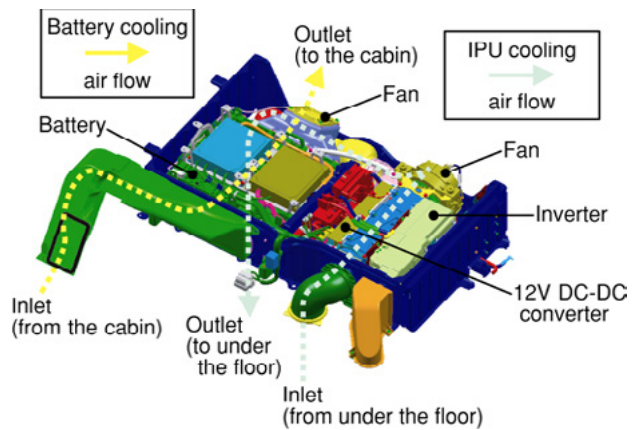


Fig. 15 Cooling air flow in Insight IPU

The cooling circuit of the Civic Hybrid IPU is shown in Fig. 16. With the Civic Hybrid, the IPU is located behind the rear seats, and the cooling air circuit is constructed so that the cooling air is taken in through an inlet placed on the rear tray in the vehicle cabin, the battery is then cooled, and the exhausted air is re-used to cool the PCU, and then the air is exhausted into the trunk space. In addition, there is no duct from the battery outlet to PCU inlet; instead one part of the IPU case is used as the cooling air circuit, which reduces the number of parts. The following were the major issues with this cooling system.

- (1) Feasibility of cooling the PCU with exhausted battery cooling air
- (2) Noise in the vehicle due to IPU cooling air
- (3) Battery temperature rise when the vehicle is left out in the blazing sun, with the battery box located vertically behind the rear seats

The verification results concerning the first issue – feasibility of cooling – are given here. Issues two and three are discussed later.

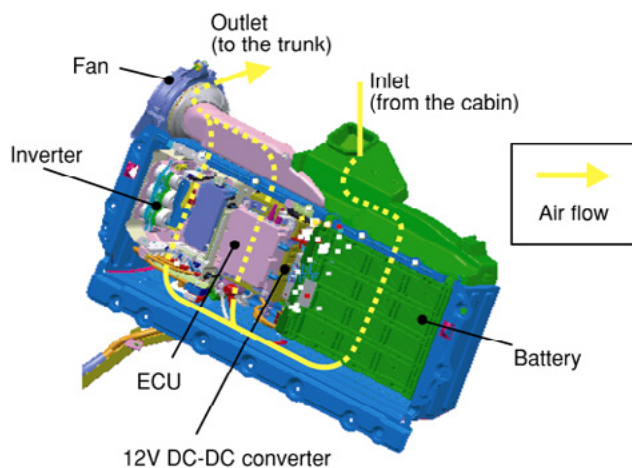


Fig. 16 Cooling air flow in Civic Hybrid IPU

4.1. Study of IPU Cooling Air Temperature

With the Insight, the PCU cooling air is taken from outside the vehicle, and under the assumption of a high temperature environment such as under a blazing sun, the highest PCU cooling intake air temperature was set at 60 °C. With the Civic Hybrid, in order to reduce the intake air temperature, the cooling systems are integrated and the battery cooling exhausted air, taken from inside the vehicle, is used, for PCU cooling. Figure 17 shows shifts in Civic Hybrid battery and PCU intake air temperatures when driving after the vehicle has been left out under a blazing sun. The rear tray intake air temperature (battery intake air temperature) drops as driving begins, and in a steady state is

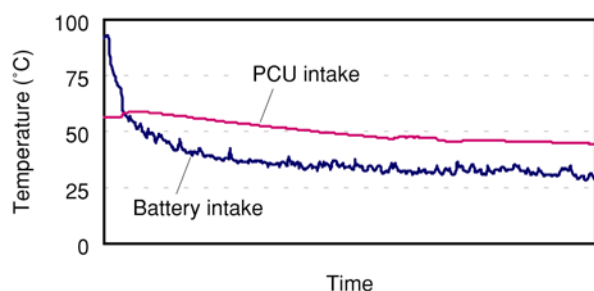


Fig. 17 Cooling air temperature when driving in hot weather

approximately 35 °C. This air temperature rises to approximately 50 °C due to the battery cooling and is used for PCU cooling. From these results, the PCU cooling air maximum temperature was set at 50 °C and a cooling feasibility study was carried out.

4.2. Study of Reducing the PCU Cooling Airflow Rate

By using the air after battery cooling to cool the PCU, it was possible to lower the intake air maximum temperature by 10 °C (to 50 °C) compared to the Insight. A study was carried out to investigate how much the required airflow rate could be reduced with this and the reduction in each component's loss mentioned earlier. As an example, Fig. 18 shows the relationship between inverter temperature and cooling airflow rate.

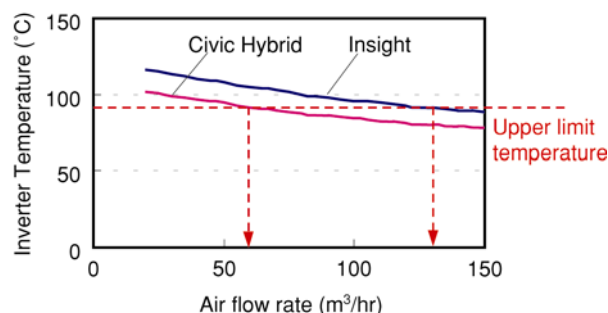


Fig. 18 Characteristics of cooling inverter

Due to a maximum loss reduction of 25% from increasing the inverter efficiency and due to a reduction in intake air temperature, the required airflow rate became 60 m³/hr, meaning that cooling is possible with an airflow rate 57% less than the previous model. In the same way, the results of studies of the 12 V DC-DC converter show that the required airflow rate is 60 m³/hr, meaning that cooling is possible with 50% less airflow than the previous model. In addition, concerning the battery, although efficiency is improved by reducing internal resistance, it is necessary to increase required cooling airflow rate by 50% to 90 m³/hr because of the increase in battery input and output accompanying the increase in vehicle body weight and regeneration energy. The results of cooling airflow rate reduction are shown in Fig. 19. As shown in this graph, against the target maximum cooling airflow rate of 90 m³/hr, all the maximum required airflow levels for battery, inverter, and 12 V DC-DC converter are at that level or less. Accordingly, it is feasible that the cooling system can cool all component parts at the maximum airflow or less which is set considering the increase in air-conditioning load and noise level inside the vehicle, etc. accompanying in-vehicle air intake and exhaust.

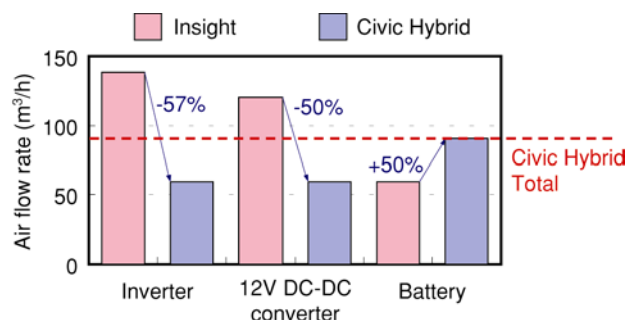


Fig. 19 Air flow rate

In this way, each component's required airflow rate is at or below the target value, and as a result of making the component devices smaller, it was possible to integrate the previous cooling circuits into one. The number of cooling fans and duct parts were also reduced, meaning that the IPU volume occupied by the cooling system was reduced by 62% over the previous model.

5. Cooling Fan Noise Reduction

Together with IMA cooling circuit integration, a PWM control type IPU cooling fan was newly developed for the Civic Hybrid. This fan can be finely controlled with no steps.



Fig. 20 IPU cooling fan

A simple method of improving cooling capability is to increase cooling airflow rate, but doing so invites the possibility of a drop in vehicle marketability due to a worsening of noise and vibration from the increase in intake airflow inside the vehicle. With the Civic Hybrid, in order to balance cooling performance and marketability at a high level, a new fan control method was developed. The larger of the following two values is selected as the fan control duty factor.

- (1) Value determined from battery temperature and input/output current value
- (2) Value determined by the difference of temperature between each battery module

In order to further reduce fan noise, control is applied according to the upper limit duty factor determined by the vehicle speed at that time. Utilizing the fact that background noise inside the vehicle changes according to vehicle speed, the fan noise discernible by the passengers must be kept to a minimum and at the same time cooling performance maintained. With the Civic Hybrid, the fan noise target value has been established to be at least 8 dB lower than the background noise inside the vehicle. Figure 21 shows vehicle speed and noise levels and Fig. 22 is a fan operation upper limit duty graph.

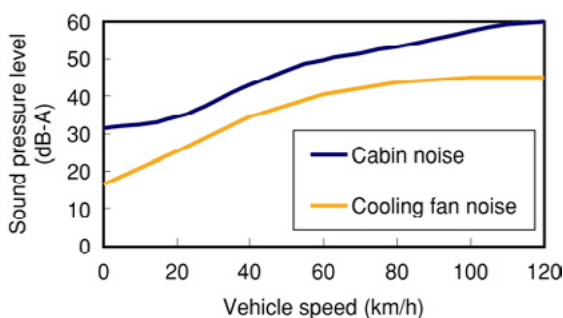


Fig. 21 Cooling fan noise

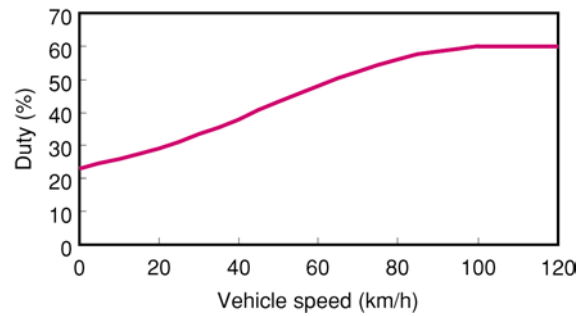


Fig. 22 Cooling fan control

By introducing the above cooling fan control, it is possible to have a cooling system that gives the necessary cooling performance while maintaining quietness.

6. Battery Module Temperature Rise Protection

By locating the IPU behind the rear seats, the battery box is placed vertically, and when the vehicle is left out in the blazing sun, the battery module at the top of the battery box is heated due to solar radiation. There can be a concern if temperature rises excessively. Therefore, with the Civic Hybrid, a heat insulator is applied around the battery box to prevent excessive battery module temperature from rising when the vehicle is left out in the blazing sun.

The major countermeasures are given below.

- (1) Place heat insulating material around the battery box
- (2) Make the intake duct out of formed resin, having insulating function, and place a hot air insulating rubber valve inside

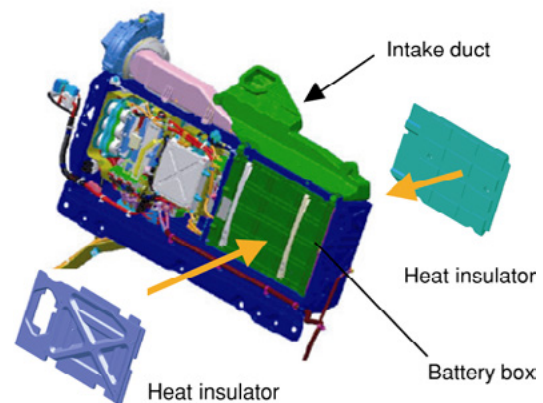


Fig. 23 Heat Insulating device for IMA battery

Through the above countermeasures, battery temperature rise during hot sun exposure is reduced by approximately 10 °C and further temperature rise at high temperatures is prevented. In addition, because these pieces are foaming expandable polypropylene beads, they provide some impact absorption and can provide some additional protection to the battery box in the event of a collision.

7. Summary

As outlined above, with the introduction of new technologies for each component, it has become possible to reduce the amount of heat generated by improving efficiency and to make each part smaller. In particular, by improving inverter and 12 V DC-DC converter efficiency, although electrical load has increased, the amount of heat generated has dropped, and for the IPU as a whole, a simplified cooling system has become possible. The two cooling circuits on the Insight IMA system were made into one. This had the effect of reducing IPU volume by 42% in comparison with the Insight. By locating the compact IPU behind the rear seats, cabin area and comfort equivalent to a conventional sedan have been maintained and it has become possible to fit the new IMA system with minimal loss of trunk space convenience.

References

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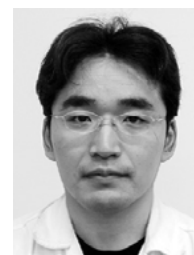
■ Authors ■



Kazuhiko AITAKA



Masaharu HOSODA



Takuya NOMURA